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MICROWAVE PUMP REQUIREMENTS FOR FIELD-OPERATIONAL BROADBAND RUTILE TRAVELING-WAVE MASERS

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ABSTRACT

This paper discusses microwave pump sources available for use in a field-operational, rutile, broadband, traveling-wave maser for the Applications Technology Satellite (ATS) program. Included is a brief resume of the current solid-state microwave pump sources, klystrons, and the Hughes and OKI backward wave oscillators. The spin Hamiltonian for iron-doped rutile is given; its solution yields a pump frequency of 54.7 GHz and pump bandwidth of 500 MHz for a 4.065- to 4.195-GHz signal frequency.

The suitability of the OKI backward-wave oscillator for the application here considered has been determined; it is simple and comparatively inexpensive to operate in the field. The solid-state modulator circuit capable of sweeping the OKI backward-wave oscillator over 500 MHz is described; and the pump package, which maintains the tube temperature at 130°F (well within the operating range required by the tube) is discussed.

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INTRODUCTION

Masers are inherently narrowband devices and, therefore, are difficult to broadband. For example, the 3-db bandwidth of a 35-db gain $Fe^{+3}\,TiO_2$ (rutile) maser is only 20 MHz. To achieve the bandwidth required by the Applications Technology Satellite (ATS), a stagger-tuning technique is employed. This represents changes in two of the major components of the amplifier: the superconducting magnet and microwave pump source. The superconducting magnet has been modified from a single field unit to a segmented structure. The magnet is comprised of seven segments that may be trimmed separately to produce a field of 1.56 kg ± 30 gauss in discrete steps. The microwave pump source, which is normally narrowband, must provide pump energy over a considerable band: 54.7 GHz ± 250 MHz for rutile, with a signal frequency of 4.065 to 4.195 GHz. These values are obtained from a GSFC computer solution of the spin Hamiltonian for $Fe^{+3}\,TiO_2$ as given in Reference 1. (References 2, 3, and 4 present a more detailed discussion of masers.)

The microwave pump requirements discussed in this paper are part of a rutile, broadband, traveling-wave maser effort of the ATS Project at Goddard Space Flight Center (GSFC). Specifications of this maser preamplifier system to be installed at the Mojave ATS station, are listed in Table 1.

One of the more critical decisions in the design of such a preamplifier system is the choice of a microwave pump source. The following discussion treats the choice of a pump source in the light of demands made on it to obtain satisfactory field operation of the preamplifier system.

Table 1

Maser Preamplifier Specifications.

Item	Value
Gain	30 db
Instantaneous bandwidth	4.065–4.195 GHz (130 MHz)
Noise temperature	10°K (max)
Phase delay	10 ns/130 MHz slope (not to exceed 1 ns/MHz)

PUMP COUPLING TO RUTILE

As noted earlier, a pump frequency of 54.7 ± 0.250 GHz is required for broadband operation at 4.065 to 4.195 GHz. Determining the amount of power required at this frequency to gain-saturate the maser is the next step. The theoretical calculation of coupling microwave energy to the maser crystal is practically impossible. Rutile is anisotropic, and its characteristics change rapidly with temperature. The most direct approach is to use empirical data compiled from many tests to find an optimum power requirement. One underlying constraint with a field-operational system is the use of a closed-cycle cryogenic system having only 1 watt of refrigeration at 4.2°K. Because of this limited capacity, excessive pump power into the maser will raise the crystal temperature and severely degrade maser performance.

The most troublesome characteristic of rutile is its extremely high dielectric constant. Trying to propagate pump energy into a material with a relative dielectric constant of 110 or 220 (depending on orientation) is tedious. This problem is further complicated by the sensitivity of the meander line circuit to its surrounding structure. For example, one technique employed in a laboratory test cavity had a waveguide attached to the top of the lid for the maser structure and a series of holes spaced periodically along the length toward the rutile. The pump coupling was good; however, the paramagnetic absorption of the structure was less than half its original value (obtained with a solid lid) and therefore was not satisfactory.

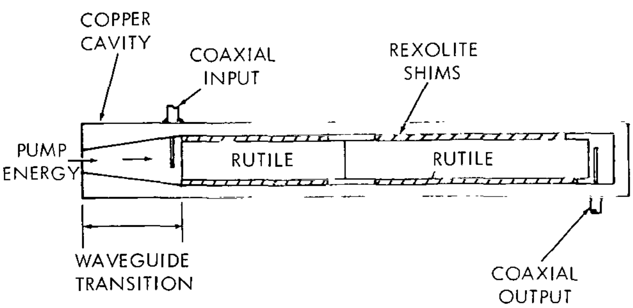

Figure 1—Maser pump coupling (top view of maser with lid removed).

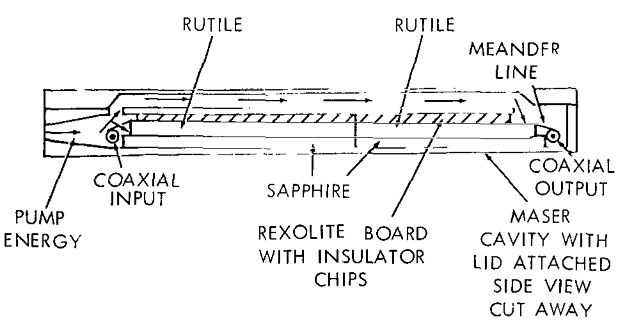

Figure 2—Maser final pump coupling (side cut away to show interior).

Initial efforts to determine a reasonable pump-coupling configuration used the design shown in Figure 1. A tapered waveguide transition helps lower the voltage standing-wave ratio (VSWR) into the cavity but due to the dielectric reflection only a small amount of the incident radiation is transmitted in the crystal. The result is that this transmitted power is absorbed in 5 inches of material. Hence it is impractical to use this type of coupling on a structure greater than 5 inches because of the demands placed on the source.

The final pump-circuit configuration chosen (Figure 2) is essentially identical to the previous coupling system, with an additional waveguide to couple the pump energy in from the rear of the cavity. With 3/4-watt input energy to the cavity, approximately 310 mw of that energy is absorbed by the rutile in a 9-inch folded maser. At this level, the maser is fully pump saturated and therefore gain stable. This configuration offers the best combination of coupling and manufacturing simplicity. Maser gain-saturation tests indicate that this circuit is more efficient than any of its predecessors.

POSSIBLE MICROWAVE PUMP SOURCES

There are several choices of a pump-power source for a broadband traveling-wave maser: a series of klystrons cascaded to give the desired power over the band required; a backward-wave oscillator (BWO) having the proper power output and sweep capability; and finally the new solid-state sources.

The first suggested source, klystrons, has been ruled out because of the number required and the size of the package required to hold and cool these units.

The BWO is currently the most promising source, since it is practically an off-the-shelf item, having the frequency, power output, and swept output capability required. However, the availability of BWO's is severely limited, since only two manufacturers build such tubes in the required range: Hughes Electronics of California and OKI Electronics of Japan. The primary characteristics of both tubes are listed in Table 2.

Table 2

Tube Characteristics.*

Hughes 381H Serial No. 40		OKI BA 54H Serial No. 117	
Item	Value	Item	Value
Filament volts	3.7 vac	Filament volts	6.3 vac
Filament current	3.6 amps	Filament current	1.02 amps
Collector volts	2.3 kv	Beam volts	3.4 kv
Collector current	40 ma	Anode volts	1.17 kv
Anode current	0.7 ma, 6.5 kv	Anode current	.02 ma
VacIon	3 kv at 0.5 microamps	Wehneldt volts	300 vdc
Cathode volts	9.5 kv	Frequency	54.35 GHz
Frequency	54.7 GHz	Power out-	850 mw
Beam power	9.5 w	Type of cooling	Water
Type of cooling	Forced air	Sweep rate	To 1 mHz
Sweep rate	To 1 mHz		

*Data from manufacturers in both cases.

The Hughes tube (Figure 3) has two advantages: surplus output power (only 310 mw is absorbed in the maser) and a VacIon pump to maintain a constant hard vacuum. However, several considerations make this tube unsuitable for use in the field-operational system contemplated here. The tube's operation requires four high-voltage power supplies, including a 9.5 kv cathode voltage supply. This, in itself, is not prohibitive, but the supply is attached to the tube case and is therefore a hazard to personnel in ordinary field operation without special precautions.

The OKI BWO (Figure 4) is reasonably easy to operate in the field. Its power output is sufficient, but not excessive, and the tube may be cooled in a fluoro-chemical oil bath without difficulty. This tube is substantially smaller than the Hughes model and is not a personnel hazard since connections are insulated from the tube body. Only three power supplies are required for tube operation.

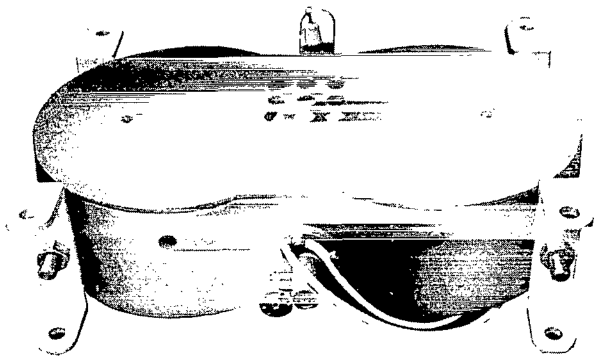

Figure 3—Hughes backward-wave oscillator.

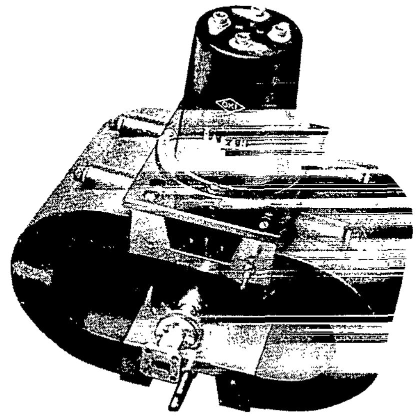

Figure 4—OKI backward-wave oscillator.

SWEPT OUTPUT FOR BROADBAND-MASER OPERATION

A plot of pump signal versus signal frequency for iron-doped rutile (Figure 5) shows that a 500-MHz pump frequency band is required for a signal frequency spread of 130 MHz. In addition, the signal and idler relaxation times determine the frequency at which the pump source must be swept to maintain a pump-saturated gain response over the maser bandwidth. It has been determined empirically that a minimum frequency of 200 kHz is required for this gain stability.

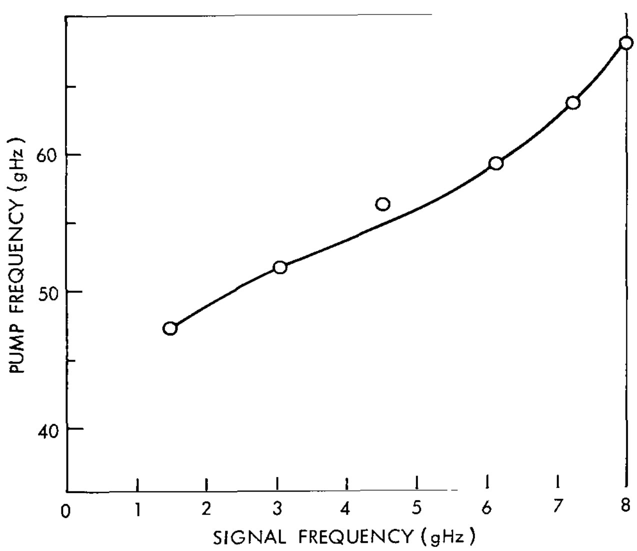

Figure 5—Pump vs. signal frequency.

The design of a compact modulator circuit has been accomplished using these criteria of 200-kHz sweep rate and 500-v modulation drive on the BWO at 1 v/MHz. This circuit is shown in Figure 6.

Transistors Q_1 and Q_2 serve as a free running multivibrator having a square-wave output at 200 kHz. Transistor Q_3 acts as a buffer amplifier to the single-stage amplifier, Q_4; Q_5 is a driver stage for the push-pull output circuit Q_6, Q_7.

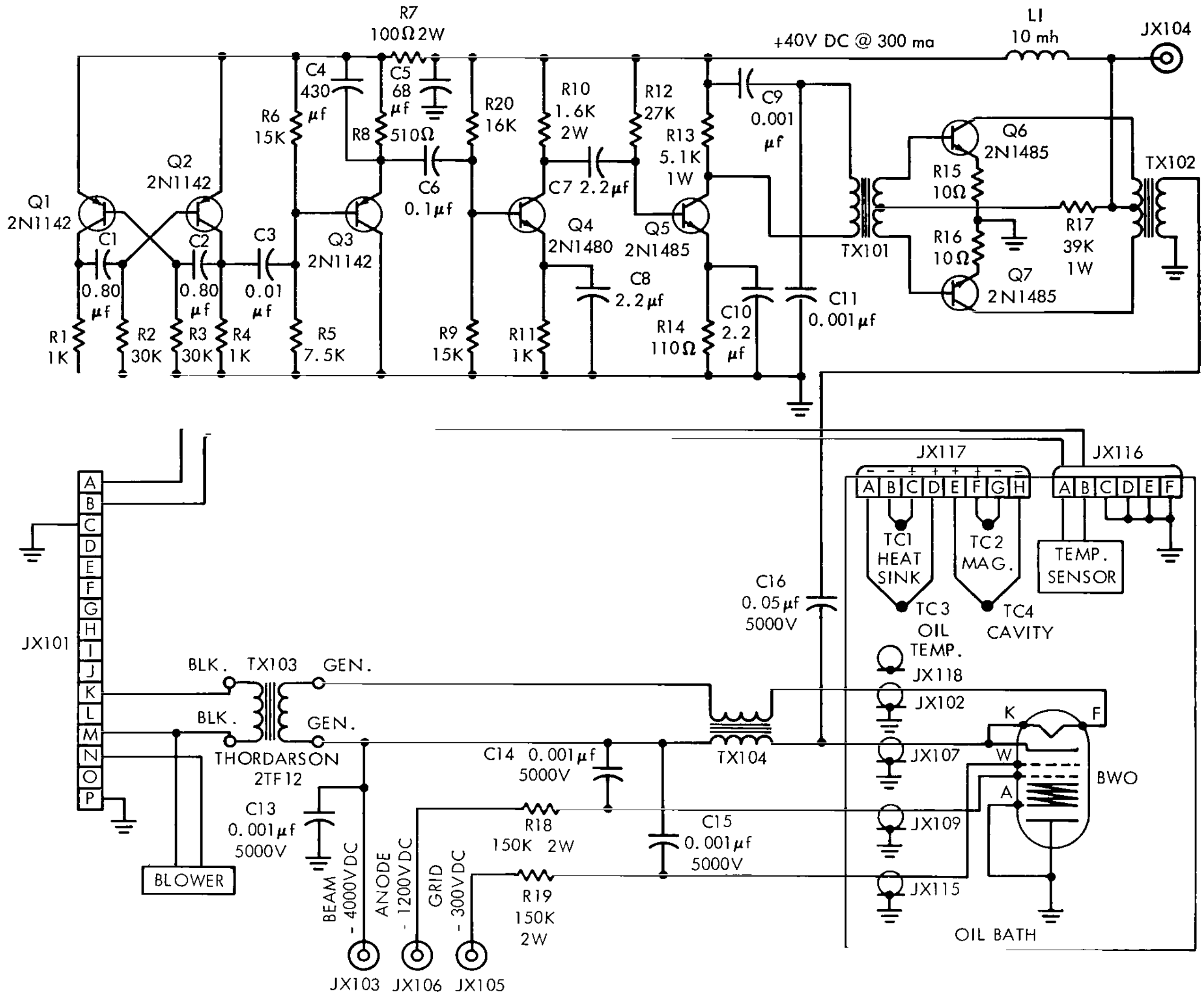

Figure 6—Compact modulator circuit.

Transformers TX101 and TX102 are specially wound, ferrite core transformers and TX101, C9, and C11 transform the square wave generated by Q_1 and Q_2 into a reasonably good sinusoid. Although 500 volts are required to sweep the BWO, sufficient output must be available to overcome the loading of the BWO and cables on the modulator. This final circuit generates 1200 volts at 200 kHz unloaded and 500 volts loaded. Reasonable care was taken to ensure the reliability of this unit for field operation. None of the transistors in this circuit approach their maximum operational capability. Transistors Q_6 and Q_7 require good heat sinks to distribute the heat generated in operation; with proper heat sinks no loss of reliability has occurred.

While there are no frequency or output controls present in the circuit itself, such controls are incorporated in the dc supply to the circuit. The unit is designed to operate with a 40-vdc power input; however, the multivibrator generates an output frequency of 200 kHz to 350 kHz, depending on the dc voltage supplied with an output level also proportional to this voltage. This characteristic is advantageous: only one control is required and the modulator may be placed adjacent to the BWO without difficulty, thereby eliminating the need for long cables carrying 200 kHz to a feed cone. If only a single sweep frequency were desired, the addition of a zener diode in the multivibrator power supply circuit (V_z = 20 volts) would fix the frequency of oscillation at 200 kHz.

PUMP COOLING AND PACKAGING

In order to utilize the BWO in a field-operational system, an oil bath was required to replace the water cooling system normally employed. A package was designed using a fluoro-chemical oil as a heat transfer agent. Typical data for the oil (FC 75) is listed in Table 3.

Figure 7 shows the final package designed and Figure 8 the temperature recorded during a thermal test of the package design.

Table 3

FC 75 Properties.

Item	Value
Boiling point	210° - 225°F
Density at 77°F	1.77 ± .02
Viscousity centistokes at 77°F	0.65 (min)
Electrical strength	35 kv (min)
Dielectric constant	1.86 (77°F)
Volume resistivity	$6 \times 10^{14}/cm^3$ (75°F)
Specific heat	0.248 Btu/161°F at 77°F

PUMP CIRCUITRY

In addition to the modulator, several additional components were added to the normal operational system to protect the tube and monitor its performance.

1. A current overload cutout was built into the beam supply to prevent an overload current from destroying the tube.
2. Thermal relays and stops were built into the tube control circuitry to prevent operation without the proper turnon times and sequence recommended by OKI.

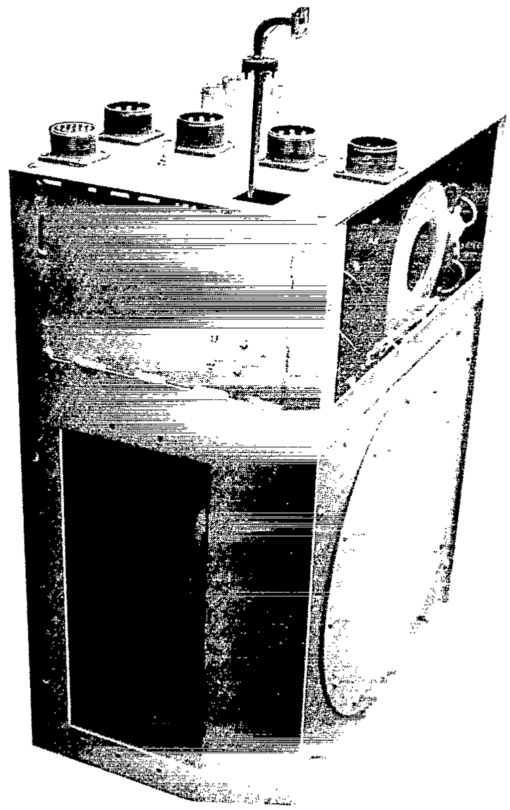

Figure 7—Complete pump package.

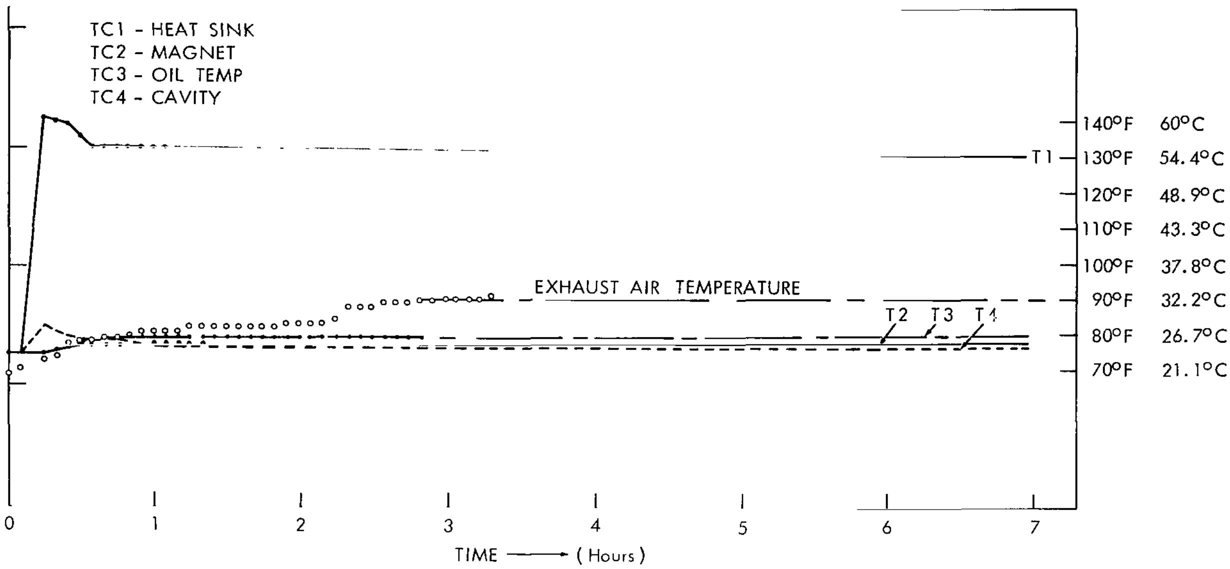

Figure 8—Pump package thermal run (backward-wave oscillator).

3. A thermostat was placed on the tube to turn off the unit if the temperature in the package exceeds 80°C.

4. A 55-GHz waveguide directional coupler detector was mounted in the waveguide circuit adjacent to the package. This unit monitors the tube output power through a dc amplifier to a meter on the control console. The meter is calibrated to read percent of maximum tube output.

With proper operation of the BWO, the tube life may be expected to exceed 1000 hours of operational time. Since the maser requires 60 percent of the tube's output power to operate, the lifetime may exceed 1500 hours. Sufficient data is available to give a reasonable lifetime value over 1000 hours.

The tube output is independent of the attitude of the package and presents no operational problems when mounted in an antenna feed cone.

SOLID-STATE PUMP SOURCES

Trends in millimeter wave sources also have a bearing to this discussion. Currently tubes are employed as the only practical source of millimeter wave energy; however, solid-state devices are evolving that may challenge tubes in future systems. These solid-state units are the Gunn oscillator and the limited space-charge accumulation (LSA) oscillator. Both units are made from gallium arsenide chips.

Two of the restrictions placed on Gunn devices are frequency output due to complications in fabrication and the inability of experimenters to remove the heat from the GaAs chip at increasing power levels. Considerable research must be performed to overcome present difficulties with Gunn devices.

The LSA units show the most promise of all the new solid-state devices. Power outputs of 20 milliwatts CW at 8 GHz and 33-w pulsed operation at 10 GHz have been reported. LSA devices are by-products of Gunn effect research and have not been specifically designed for LSA operation. Since the LSA diodes are somewhat easier to fabricate than Gunn devices, they may overshadow other solid-state oscillators in the maser pump field. Considerable interest has been shown in finding a solid-state unit to replace the BWO for maser pump use. If this is achieved, considerable economy and simplicity of masers will result.

ACKNOWLEDGMENTS

The author wishes to acknowledge the work of Mr. John K. Jones, GSFC, for the mechanical design of the BWO package and electrical switching circuitry and Mr. Carl Riffe, Lockheed Electronics Company, for the thermal design of the BWO oil bath.

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National Aeronautics and Space Administration
Greenbelt, Maryland, February 6, 1968
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